

Broadly tunable second-harmonic generation in periodically poled silica fibers

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Broadband tunability of the second-harmonic wavelength is achieved in periodically poled silica fibers. A wavelength tuning range of almost 45 nm of the fundamental wave is demonstrated through mechanical compression tuning of the quasi-phase-matched periodic structure. The uniform strain applied along the entire periodic structure enables the spectral profile and the conversion efficiency of the generated second harmonic to be preserved for the full tuning range. To our knowledge, the achieved tuning range realized through this technique is far greater than that possible with uniform periodically poled crystals. © 2007 Optical Society of America

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Amorphous silica is intrinsically void of a second-order nonlinearity (SON) due to its macroscopic inversion symmetry. A technique widely referred to as thermal poling can be utilized to break this symmetry to introduce an effective SON into the glass matrix. In the process of thermal poling, the sample is heated to an optimum temperature while a high DC electric field is applied. The high temperature mobilizes ions, while the electric field relocates these ions, causing a region, depleted of like charges, to form near the anode. The sample is cooled to room temperature while the electric field is still applied, enabling the electric field to be frozen in. This frozen-in field combines with the inherent third-order nonlinearity of the glass to produce an effective SON. SON values as high as 1 pm/V have been reported in the literature for bulk silica [1]. However, high values of SON have not been consistently achieved in fibers as the electro-optic effect induced is affected by many factors, such as fiber geometry and core composition [2]. The induced SON can be exploited to fabricate devices dependent on the SON, such as frequency converters, electro-optic modulators/switches, and optical parametric oscillators. Silica fiber poling for second-harmonic generation (SHG) is particularly attractive as it offers considerable advantages over bulk materials, such as longer interaction lengths, compensating for the relatively low SON, and straightforward integration with all-fiber systems. The phase-velocity mismatch between the fundamental and generated second-harmonic (SH) waves can be compensated through quasi-phase matching [3] (QPM). In this Letter, QPM is realized through a relatively new technique of ultraviolet periodic erasure of the induced SON in uniformly poled fibers [4].

Wavelength tuning of fiber Bragg gratings (FBGs) using mechanical compression has been recognized as the best solution to date for achieving very large tuning ranges [5]. The high endurance of silica based fibers to high compressive stresses allows efficient broadband tuning of FBGs encompassing the *S*, *C*, and *L* bands, translating to a tuning range of 110 nm [5]. In this Letter, broad wavelength tuning of the generated second-harmonic light is demonstrated

through mechanical compression of the periodic QPM structure. Thus the functionality of the periodically poled silica fiber (PPSF) is further increased with wavelength tuning, for example, enabling broadband frequency conversion of tunable fiber laser sources. Additionally, tunable optical parametric oscillators should also be possible in fibers.

A specially designed silica fiber of 0.20 NA was fabricated with two holes of 43 μm diameter on either side of the germanium-doped core (3.6 at. %). The geometry of this is shown in Fig. 1. The holes can accommodate 25 μm electrodes (gold-coated tungsten) for the application of the electric field. One of the holes was intentionally positioned closer to the core to attain an improved overlap with the induced nonlinear layer that is formed around the anode electrode hole during the thermal poling process. For the purpose of *in situ* measurement of the $\chi^{(2)}$ during poling, the electrodes are inserted into polished holes through the sides of the fiber, so that the ends can be fusion spliced into one arm of an all-fiber Mach-Zehnder interferometer. Thus the growth of the induced SON is monitored by the online measurement of the electro-optic coefficient through the change in phase in the fiber device during thermal poling [6,7]. Thermal poling was carried out at a previously deter-

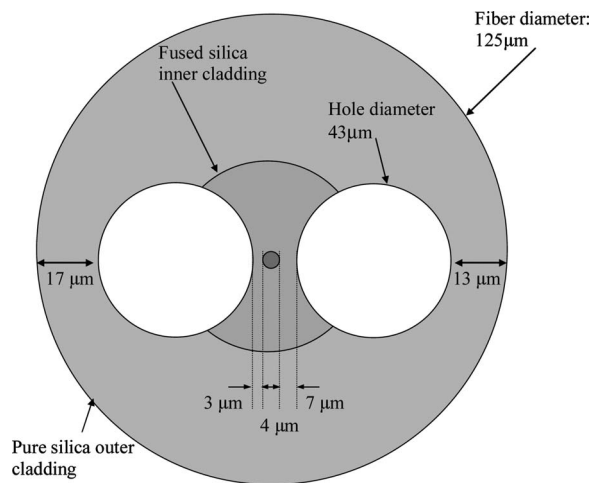


Fig. 1. Schematic of the twin-hole fiber used for this work.

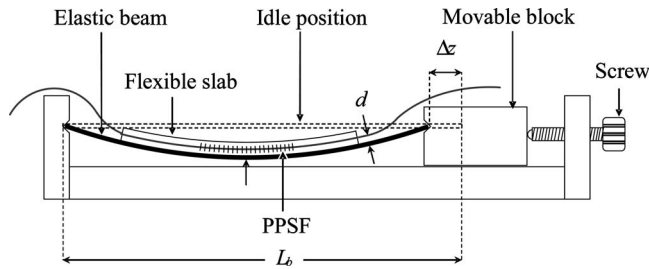


Fig. 2. Compression tuning package used for wavelength tuning of the PPSF device.

mined optimal temperature of 330°C and a DC voltage of 3.5 kV. A residual $\chi^{(2)}$ value of ~ 0.15 pm/V was measured for the PPSF devices used for this experiment.

After poling, the electrodes are removed and the poled section of the fiber is spliced onto standard telecommunications fiber for periodic erasure. The poled devices are then periodically erased using a frequency-doubled argon-ion laser at predetermined QPM periods. The characterization of the PPSF devices is performed with a high-power pulsed fiber laser source delivering 10 ns pulses at a repetition rate of 450 kHz. The source consists of a seed laser followed by a series of cascaded fiber amplifiers in a master oscillator power amplifier (MOPA) configuration. The source produces high power in the erbium-gain range and a lower power supercontinuum in the 1400–1600 nm range. A conversion efficiency of $\sim 6\%$ was achieved for a PPSF device of length 12 cm, utilizing 140 mW of average power from the MOPA. This PPSF device had a QPM period of 52.7 μm , which in this particular fiber corresponds to a fundamental wavelength of ~ 1543.1 nm, well within the high-gain region of the source.

For the wavelength tuning experiments, a 4 cm long PPSF device was fabricated from the same fiber at a period of 53.7 μm , corresponding to a fundamental wavelength of ~ 1594.5 nm. This PPSF device was wholly embedded in a composite beam, consisting of a baseplate of high tensile steel and two layers of polymeric material with disparate Young's modulus values. The beam containing the PPSF device was then mounted on a purpose-built stage, in between a fixed block and a moveable block, as seen in Fig. 2. During tuning, the inward translation of the moveable block causes the beam to deform into a circular arc shape. The sector angle (θ) formed by the beam determines the strain experienced by the PPSF device. The wavelength shift of the fundamental pump wave, $\Delta\lambda$, is given by

$$\begin{aligned}\Delta\lambda &= (1 - \rho_e) \cdot \varepsilon \cdot \lambda_f, \\ &= 0.78 \cdot \left(\frac{d \cdot \theta}{L_b} \right) \cdot \lambda_f,\end{aligned}\quad (1)$$

where ε is the strain, λ_f is the fundamental wavelength in idle state, L_b is the length of the beam, d is the distance of the PPSF device from the center of the

baseplate, and ρ_e is the photoelastic constant of the optical fiber.

Due to the lack of a broadly tunable fundamental pump source of sufficient power, the characterization of the generated second harmonic during tuning was performed using the broadband supercontinuum generated by the aforementioned fiber laser source. The wavelength spectrum of the source is shown in Fig. 3. The spectrum of the generated SH wave was captured with an optical spectrum analyzer after each compressive tuning adjustment.

Figure 3 shows the SH spectral profiles for a range of compressive strain values. The SHG spectrum, measured when no strain is applied to the QPM grating, is indicated as the idle point. The spectra to the left of the idle point were measured for increasing compressive strain tuning. As the power of the supercontinuum source used for characterization is not consistent across its spectral range, the generated SH power also fluctuates. The quadratic relationship between the SH power and the fundamental pump power further accentuates the SH signal variation. The inherent birefringence of the twin-hole fiber results in two slightly different phase-matching conditions between the orthogonal polarization states in the fiber, giving rise to two SH peaks of slightly different center wavelengths. The polarization of the fundamental wave was initially adjusted at the idle point to extinguish the second (weaker) SH signal. However, during the course of the experiments, the polarization state of the fundamental wave was seen to drift, as evidenced by the presence of a weaker SH signal from the other polarization state. The shoulder peak seen alongside the stronger peak in the profiles to the left of the idle-state profile is thus attributed to the contribution from the orthogonal polarization state. This drift also causes a reduction in the power of the primary SH peak as seen with further tuning. The acceptance bandwidth of the generated SH light was measured to be ~ 4.65 nm for this 4 cm PPSF device, in agreement with theoretical predictions. In

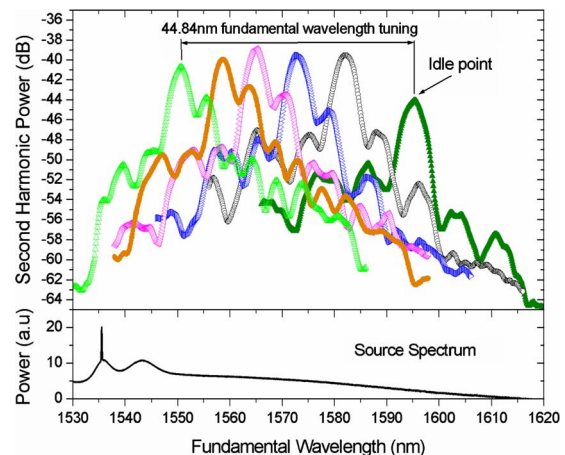


Fig. 3. (Color online) SH power measured as a function of the fundamental wavelength for the 4 cm PPSF device. Only 6 profiles from a total of 26 taken are shown for clarity. The idle point indicates the SH spectrum of the PPSF device prior to tuning. The lower graph shows the wavelength spectrum of the fundamental source.

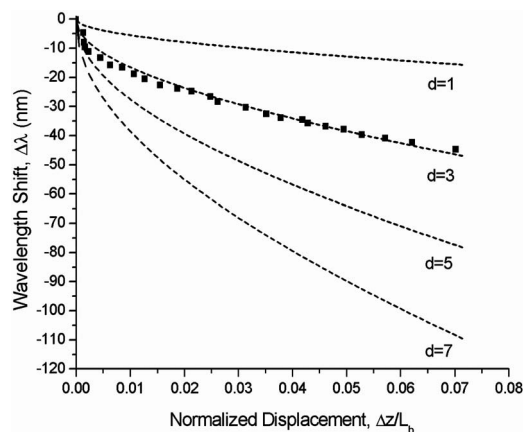


Fig. 4. Fundamental wavelength shift plotted against the normalized horizontal displacement for different values of d ; dotted curves indicate theoretical and black boxes indicate actual measured values.

the first experiments a maximum tuning range of ~ 45 nm in the fundamental wavelength was obtained, limited by the travel range of the compression tuner used. Further attempts to increase this range using a second tuner resulted in the breakage of the device. The short travel stage could still be used for further tuning if the distance (d) from the fiber to the baseplate in the composite beam is increased.

Figure 4 shows the relationship between $\Delta\lambda$ and the normalized displacement, $\Delta z/L_b$, for various values of d (see Fig. 2). The data points show the actual experimental values obtained for wavelength tuning of the 4 cm PPSF device. The experimental data are in good agreement with theoretical curves for the $d = 3$ mm case, demonstrating that the wavelength can be precisely controlled. It can be seen from the theoretical curves of Fig. 4 that larger values of d allow broader tuning for the same displacement. The ~ 45 nm shift in the fundamental wavelength is obtained with a normalized displacement of 0.07 in the compression mode. While it is a significant improvement over the ~ 28 nm reported previously [8], it still falls short of the 110 nm achieved in FBGs through compression tuning. The reasons for this shortfall are attributed to the fragility of the twin-hole fiber used for this work and to the presence of two splice points inside the composite beam. The splice points also prevented tuning of the device in extension mode, as had been done with FBGs, to further extend the tuning range [9]. It should be possible to further increase the SH tuning range by placing the splice points outside the beam and/or by utilizing twin-hole fibers more resilient to axial stresses. The axial strength could be improved by revising the geometrical design of the present twin-hole fiber.

A tuning range of ~ 45 nm of the fundamental wavelength in a uniform-period PPSF is far greater than that possible with uniform periodically poled crystals. A wavelength tuning range of 7 nm (SH) was reported in periodically poled lithium tantalate [10]. This range was achieved through temperature tuning of the crystal, with 240°C required to reach a

change of 14 nm in the fundamental wavelength. The impracticalities associated with the large temperature variation required to achieve this tuning range suggest that this technique is more suited for fine tuning of the SHG wavelength rather than broad tuning. In PPSF broadband tuning is possible purely through compressive tuning, enabling a wide range of SHG wavelengths to be accessed using a single device. The PPSF device can be maintained at room temperature, preserving the induced SON, which in turn ensures a stable and consistent SH signal. The lower second-order nonlinearity of PPSF devices can be compensated through longer interaction lengths. The inherently lower chromatic dispersion in fibers allows much longer interaction lengths, while offering comparable acceptance bandwidths with that of shorter crystals such as lithium niobate. Further, lower propagation losses and lower insertion losses coupled with a high optical damage threshold, make PPSFs a viable alternative to bulk crystalline devices for frequency-doubling applications.

PPSFs are ideal for the frequency doubling of high-power, ultrashort pulse fiber laser sources, owing to the high damage threshold and the straightforward adaptability to all-fiber systems. The practicalities of a PPSF for frequency doubling have been furthered by the addition of wavelength tunability. The tuning range of almost 45 nm of the fundamental wavelength is to our knowledge the largest reported for SH wavelength tuning of a device of a single QPM period. This range can be further extended by improving the axial strength of specialty fibers used for poling.

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